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Toughness Envelope Definition of Pulsed Gas Metal Arc Welds in HY80 Steel

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Contract #W7707-0-8370

Defence R&D Canada

Contractor Report
DREA CR 2001-085
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H/DL(A)

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Abstract

Over the past decade, Defence Research Establishment Atlantic (DREA) has sponsored several projects related to "All Position Gas Metal Arc Welding" as part of their mandate to develop expertise in submarine materials and maintenance technology. These efforts have led to the identification of pulsed GMAW with C5, C10, or T.I.M.E. gas combinations as the preferred ones from the perspective of superior weld zone mechanical properties in HY steels.

Previous work was successful in ranking new digital pulsed gas metal arc welding systems for optimal introduction in submarine refit followed by the development of a low heat input benchmark welding procedure for welding HY-80 steel in the vertical-up position, using Lincoln's LA100 (ER100S-1) solid wire with T.I.M.E. gas (26.5%He, 8%CO_2, 0.5%O_2, and Argon bal.).

Although the benchmark is considered a practical procedure for the purposes of submarine repair and modification, it would be advantageous from the point of view of productivity to increase the heat input while maintaining the toughness requirements.

Five welded panels were produced with ER100S-1 solid wire and T.I.M.E. gas, and radiographed +/- 20° to normal to verify weld soundness. The heat input used to produce each welded panel spanned the practical range for all position welding with the objective of identifying a level at which the weld metal toughness drops off below the required value. Dynamic tear samples were extracted and tested to develop notch toughness transition curves for each weld heat input.

Résumé

Au cours de la dernière décennie, le Centre de recherches pour la défense Atlantique (CRDA) a parrainé divers projets de « soudage MIG toutes positions » dans le cadre de son mandat pour développer l'expertise en matériaux de sous-marin et en technologie de maintenance. Ces efforts ont mené à l'identification du soudage MIG par impulsions avec des combinaisons de gaz C5, C10, ou TIME comme les plus aptes à garantir des propriétés mécaniques de zone de soudage supérieures avec les aciers HY.

Les recherches précédentes ont permis de classer le nouveau système de soudage TIG par impulsions numériques pour une introduction optimale des travaux de radoub de sous-marins, suivi par le développement d'une procédure à faible apport de chaleur utilisée comme valeur repère pour le soudage de l'acier HY-80 en position verticale avec du fil plein Lincoln LA100 (ER100S-1) combiné avec du gaz TIME (26,5 % He, 8 % CO_2, 0,5 % O_2 et Argon).

Bien que la valeur repère soit considérée comme une procédure pratique pour les réparations et les modifications de sous-marins, il serait avantageux du point de vue de la productivité d'augmenter l'apport de chaleur tout en conservant les exigences de ténacité.

Cinq panneaux soudés avec du fil plein ER100S-1 et du gaz TIME ont été radiographiés à +/- 20° de la normale pour vérifier la qualité des soudures. L'apport de chaleur utilisé pour souder les panneaux a accru la portée pratique du soudage toutes positions avec pour objectif d'identifier le niveau où la ténacité du métal soudé se trouve sous la valeur requise. Des échantillons de déchirures dynamiques ont été prélevés et testés pour mettre au point la résistance des courbes de transition de la ténacité aux entailles pour chaque apport de chaleur de soudage.

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Executive summary

Previous investigations carried out at DREA and on its behalf have demonstrated that the gas metal arc welding (GMAW) process using selected electrode wires and shielding gases provide high strength weld metal with superior toughness in submarine steels than is the case for the shielded metal arc (SMA) and flux cored arc (FCA) welding process.

Over the time period of the previous DREA sponsored projects, there had been concurrent development and availability of advanced power sources with digital pulsing technology With the use of such power sources, GMAW arc stability has become considerably enhanced and therefore making sound welds in welding positions other than flat position much easier. After a recent study conducted by Fleet Technology Limited, the Lincoln Powerwave 450 was ranked as the optimum digital pulsing power source for P-GMA welding, closely followed by a Miller machine

In benchmark welding with the recommended welding machine, the low heat input (0 64 to 1 0 kJ/mm, average 0.89 kJ/mm) benchmark P-GMAW and T I M E gas combination demonstrated superior weld metal strength and toughness properties compared to P-MCAW and SMAW To that end, it was decided that a toughness envelope be defined for the P-GMAW process, based on heat input, so that an operating range which produces sound welds could be specified for "out-of-position" welding during submarine repair and modifications.

Five 25 mm thick HY-80 panels were fabricated in the vertical-up position with Lincoln's 1 2 mm LA100 (ER100S-1) solid wire and T I M E gas using a Miller Phoenix machine Each panel was welded with weld passes of a constant heat input 0 5, 0 7, 0 9, 1 1, and 1 4 kJ/mm

The radiography results showed that the 0 7, 0.9, 1.1, 1.4 kJ/mm panels were free of cracks and lack of fusion type indications, however, the 0 5 kJ/mm panel contained sporadic lack of fusion type indications. It is likely that the high travel speed and reduced wetting action of the weld pool at the 0 5 kJ/mm heat input level was the cause of the lack of fusion flaws, and, this level of heat input is not recommended for this application.

Five nominally full thickness dynamic tear specimens were machined from each weld heat input and were notched in the through thickness orientation at the weld centerline as per ASTM Standard E604 and tested at the Dockyard Laboratories (DREA).

It was concluded that

(a.) Based on the shear lip results, there is a downward trend in toughness around 1 kJ/mm
(b) Based on visual appearances, the 0 5 and 0.7 kJ/mm weld metals are tougher than at other heat inputs with the 0.5 kJ/mm weld being the toughest.
(c) All welds produced in this project exceeded the minimum 690 J at -30°C CF toughness requirement.
(d.) Although the 0.5 to 1.0 kJ/mm heat input range produced the best toughness over the range of heat inputs tested, the heat input range of 0 7 to 1 1 kJ/mm tested provides the best operating range for 3G vertical-up welding with the Miller Phoenix power source.

Based on the findings in this project, it was recommended to. Evaluate the weld metal toughness in the other positions (flat, horizontal, and overhead)

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Sommaire

Lors d'études précédentes effectuées au CRDA ou pour son compte, il a été démontré que le procédé de soudage MIG effectuée avec certains fils-électrodes et un gaz de protection produit des soudures à haute résistance présentant une ténacité supérieure pour les aciers des sous-marins que si on utilise des procédures de soudage à l'arc avec électrode enrobée et ou de soudage à l'arc avec fil fourré

Depuis les derniers projets parrainés par le CRDA, des développements concurrents et la disponibilité de sources d'alimentation avancées relevant de la technologie par impulsions numériques sont apparus. Avec l'utilisation de ces sources d'énergie, la stabilité de l'arc de soudage MIG a été considérablement renforcée et produit par conséquent des soudures en positions aussi solides que celles à plat. Suite à une étude récemment effectuée par Fleet Technology Limited, le Lincoln Powerwave 450 est apparu comme la source d'énergie par impulsions numériques optimale pour le soudage MIG-I, suivi de près par la machine Miller

Avec comme repère de soudage pour la machine à soudage recommandée une faible production de chaleur (0,64 à 1,0 kJ/mm, avec une moyenne de 0,89 kJ/mm) pour le soudage MIG-I combiné avec du gaz TIME, une résistance de soudure supérieure et des propriétés de ténacité plus forte ont été obtenues comparativement avec les procédures MCAW-I et de soudage à l'arc avec électrode enrobée À cette fin, il a été décidé qu'une enveloppe de ténacité soit définie pour la procédure de soudage MIG-I, basée sir l'apport de chaleur, de façon à ce qu'une plage d'utilisation produisant des soudures solides puisse être spécifiée pour le soudage « hors-position »lors des réparations et des modifications sous-marin

Cinq panneaux HY-80 de 25 mm d'épaisseur ont été soudés en position verticale au moyen d'un fil plein Lincoln de 1,2 mm LA100 (ER100S-1) et de gaz TIME avec une machine Miller Phœnix Les panneaux ont été soudés avec des passes de soudure de chaleur constante de 0,5 kJ/mm, 0,7 kJ/mm, 0,9 kJ/mm, 1,1 kJ/mm et 1,4 kJ/mm.

Les résultats des radiographies ont démontré que les panneaux de 0,7 kJ/mm, 0,9 kJ/mm. 1,1 kJ/mm et 1,4 kJ/mm ne présentaient pas de fissures ou d'indices de manque de fusion Mais le panneau de 0,5 kJ/mm présentait des indices sporadiques de manque de fusion. La rapidité d'exécution des passes et l'action de mouillage réduite du métal liquide à un niveau de 0,5 kJ/mm entraînant vraisemblablement le manque de défauts de fusion, ce niveau d'apport de chaleur n'est pas recommandé pour cette application.

Cinq déchirures dynamiques en pleine épaisseur ont été usinées avec chaque apport de chaleur de soudage. Les entailles ont été pratiquées dans le sens de l'épaisseur au centre de la soudure conformément à la norme ASTM E604 et testées aux laboratoires du chantier naval (CRDA)
Conclusions :

(a) À la lumière des résultats de cisaillement de lèvre, la ténacité à tendance à baisser autour de 1 kJ/mm

(b) Visuellement, les soudures effectuées à 0,5 kJ/mm et 0,7 kJ/mm semblent plus résistantes que celles obtenues avec d'autres apports de chaleur, la soudure de 0,5 kJ/mm semblant la plus résistante

(c) Les soudures produites dans cette étude dépassent la valeur minimale des exigences de ténacité des FC qui est de 690 J à -30°C.

(d.) Bien que la plage d'apport de chaleur de 0,5 à 1,0 kJ/mm produise la meilleure ténacité de toute la plage d'apport de chaleur testée, la portée d'apport de chaleur de 0,7 kJ/mm à 1,1 kJ/mm testée donne les meilleurs résultats avec les soudures 3G verticales obtenues avec la source d'énergie Miller Phœnix.

Compte tenu des résultat obtenus dans le cadre de cette étude, il est recommandé d'évaluer la ténacité des soudures dans les autres positions (à plat, horizontale et en hauteur)

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1. INTRODUCTION

Previous investigations carried out at DREA and on its behalf have demonstrated that the gas metal arc welding (GMAW) process using selected electrode wires and shielding gases provide high strength weld metal with superior toughness in submarine steels than is the case for the shielded metal arc (SMA) and flux cored arc (FCA) welding process.

Over the time period of the previous DREA sponsored projects, there had been concurrent development and availability of advanced power sources with digital pulsing technology. With the use of such power sources, GMAW arc stability has become considerably enhanced and therefore making sound welds in welding positions other than flat position much easier. After a recent study conducted by Fleet Technology Limited, the Lincoln Powerwave 450 was ranked as the optimum digital pulsing power source at the time for P-GMA welding, closely followed by Miller's Maxtron 450 with 60M digital feeder.

At the same time, newer electrode wires were being developed to further enhance weld zone properties and enable welding productivity to be increased. Use of metal cored wires instead of solid wires in the GMAW process was one promising approach in this context. To evaluate such newer consumables however, benchmark welding procedures were established against which comparisons were made. Two welded panels were fabricated from HY-80 at low heat inputs using a state of the art digital pulsed welding power source (Lincoln Powerwave 450) and two electrode wire-shielding gas combinations i.e. Lincoln's LA100 (ER100S-1) and T.IM.E. (26.5%He, 8CO_2, 0.5%O_2 and Argon bal.) gas, and, Lincoln's MC100 and M2 (2%O_2 and Argon bal) gas.

The low heat input (0.64 to 1.0 kJ/mm, average 0.89 kJ/mm) benchmark P-GMAW and T.I.M.E. gas combination demonstrated superior weld metal strength and toughness properties compared to the benchmark P-MCAW and M2 procedure (1.2 to 2.4 kJ/mm, average 1.83 kJ/mm heat input). To that end, it was recommended that a toughness envelope be defined for the P-GMAW process, based on heat input, so that an operating range which produces sound welds could be specified for "out-of-position" welding during submarine repair and modifications.

2. APPROACH

The approach was to weld five 1000 mm long 25 mm thick HY-80 panels in the 3G vertical-up position with 1.2 mm diameter ER100S-1 (Lincoln LA100) and T.I.M.E. gas. The heat input was increased with each subsequent panel welded, and, the heat inputs used spanned the range suitable for 3G vertical-up welding. The Miller Phoenix and 60M digital feeder was used to perform all welding in this project to ensure that the results obtained in this project were repeatable with the Miller Phoenix power sources currently in use at the Fleet Maintenance Facility (FMF) Cape Scott, in Halifax, Nova Scotia.

The goal was to fill up an entire panel joint with weld passes of a constant heat input. Each subsequent panel was welded at an increased heat input in order to evaluate its effect on weld metal toughness. Through laboratory trials, several beads were deposited in vee-groove joints to determine what range and combination of wire feed speed, voltage or "trim", travel speed, and contact tip to work distance provided the best performance in terms of "wetting ability", weld pool control, and weld appearances.

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It was found that if the heat input was adjusted below 0.5 kJ/mm there was a dramatic loss in "wetting action" and would likely result in lack of fusion type flaws. Also, it was found that if the heat input was adjusted above 1.4 kJ/mm there was a dramatic loss in weld pool control resulting in welds with very convex profiles which required substantial interpass grinding. Therefore, the range of heat inputs that were tested was 0.5 to 1.4 kJ/mm, and, the heat input levels were 0.5, 0.7, 0.9, 1.1, and 1.4 kJ/mm.

The finalized welding procedures were then used to make the test welds, and after their non-destructive examination, the following specimens were extracted from each weld with the objective of assessing weld metal hardness and toughness properties:

(a) One cross section for macro-examination and hardness testing;
(b) Five dynamic tear specimens per heat input notched along the weld centerline;
(c) Two dynamic tear specimens per heat input notched in the heat affected zone.

3. INVESTIGATION AND RESULTS

3.1 Weld Fabrication

All panels were fabricated using a double vee-groove configuration with equal groove depths. Although a 60° included angle was commonly used in past projects, it was decided to increase this angle to 70° to provide improved accessibility for the welding gun thus reducing the chances of lack of fusion type flaws. The root consisted of a "feather edge" preparation, in which no root face was used, and a round ceramic backing strip was incorporated into the back side of the 1st root pass. This method gave sufficient penetration into the 2nd side which kept the depth of back-grinding for the 2nd root pass to a minimum. A balanced welding approach, in which the weld layers were alternated from side to side, was adopted to minimize distortion.

Before commencing welding, the groove and adjacent base plate were preheated, using resistance heating elements, to a temperature of 90°C as required by the Canadian Navy Submarine fabrication specifications. However, the interpass temperature was maintained at a relatively low value of 120°C in order to prevent potential deleterious effects of higher interpass temperatures on weld metal strength and toughness.

In order to deposit all weld passes in a given panel at the selected constant heat input, amperage and voltage were monitored with real time data acquisition and were adjusted accordingly by a "third hand" to ensure consistency. Though the welding gun was manipulated by hand, as would be done in a semi-automatic application, a mechanized travel carriage was used to guide the welding gun along the length of the joint at a predetermined rate to maintain a constant travel speed and thus the desired heat input.

While no postweld-heating was applied, the completed welds were immediately covered with thermal blankets as a precautionary move to minimize the risk of hydrogen induced cold cracking in the weld zone.

The detailed welding procedures employed are outlined in Welding Procedure Data Sheets in Appendix A

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3.2 Non-Destructive Examination

The non-destructive examination comprised of visual examination for surface flaws, followed by radiography to evaluate the weld metal for soundness and ensure that the dynamic tear samples were taken from an area away from potential defects that could skew the results.

The visual examination revealed no significant undercut and the weld reinforcement ranged from 3 mm for the 0.5, 0.7, and 0.9 kJ/mm heat input welds, to 6 mm for the 1.1 and 1.4 kJ/mm heat input welds. The 6 mm cap height for the 1.1 and 1.4 kJ/mm welds exceed that allowable for acceptable practice, however, the goal was to keep the number of passes and the deposition sequences the same for all panels so there were no discrepancies between the weld metal results.

The radiographic examination included two shots taken of each weld heat input, at +/- 20° to the normal. The results showed that the 0.7, 0.9, 1.1, 1.4 kJ/mm panels were free of cracks and lack of fusion type indications, however, the 0.5 kJ/mm panel contained sporadic lack of fusion type indications and this type of weld quality would not be suitable for submarine pressure hull welding. There were small areas of clustered porosity in each panel which were associated with weld "stop-start" locations, likely a result of operator error.

3.3 Mechanical Property Test Results

Hardness

All hardness readings were obtained on one cross section prepared from each weld heat input (see **Figure 3.1**) using Vicker's hardness testing equipment and a 5 kg load. The hardness traverses were performed so as to obtain the average weld metal hardness along the weld centerline to the corresponding dynamic tear weld metal notch location. The results obtained are summarized in **Table 3.1** and are plotted in **Figure 3.2**.

0.5 kJ/mm **0.7 kJ/mm** **0.9 kJ/mm** **1.1 kJ/mm** **1.4 kJ/mm**

Figure 3.1: Typical Weld Cross Sections for Each Heat Input

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Table 3.1: Vickers Hardness Results, 5 kg Load

Heat Input (kJ/mm)	Hardness Range (HV)	Average Hardness (HV)
0.5	255 to 332	291
0.7	233 to 328	287
0.9	238 to 280	260
1.1	244 to 300	275
1.4	175 to 319	253

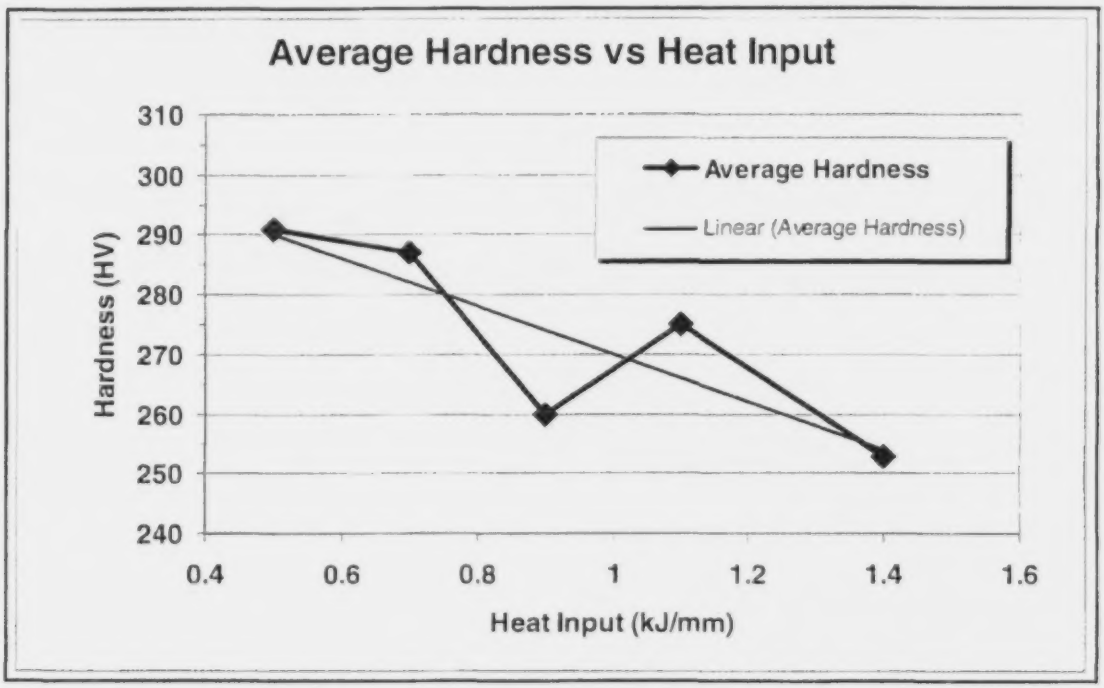

Figure 3.2: Hardness vs. Heat Input

The above hardness results show an overall trend in decreasing hardness with increasing heat input. One possible reason for this is that the low hardness at high heat input is related to the presence of coarser, softer microstructure (either ferrite or lower bainite) forming from higher transformation temperatures and slower cooling rates, and, the high hardness at low heat input is related to finer, harder microstructures (primarily martensite) forming from low transformation temperatures and faster cooling rates. It is also likely that the degree of tempering of previously deposited welds increases with increasing heat input thus resulting in a softer weld metal. However, in order to make any solid conclusions on the effect heat input has on weld metal microstructure and hardness a full metallurgical evaluation is suggested.

Dynamic Tear Tests

Five nominally full thickness dynamic tear specimens were machined from each weld heat input panel and were notched at the weld centerline as per ASTM Standard E604. Although the 0.5

kJ/mm weld contained sporadic lack of fusion, the five dynamic tears were removed from reasonably clean locations. Two additional dynamic tear specimens were machined from each weld heat input and were notched in the heat affected zone at the mid thickness location. All specimens were tested at the Dockyard Laboratories (DREA) and the results are shown in **Tables 3.2, 3.3, and 3.4,** and, **Figures 3.3, and 3.4**.

Table 3.2: Weld Metal Notched Dynamic Tear Energy

	Heat Input (kJ/mm)				
	0.5	**0.7**	**0.9**	**1.1**	**1.4**
Temp (°C)	**Weld Metal Dynamic Tear Energy (J)**				
-10	1692	2143	1455	2010	1644
-20	1101	2023	1344	1232	969
-30	1408	1144	951	1375	1031
-40	837	834	754	976	943
-47	884	915	894	859	740
Average	1184	1412	1080	1290	1065

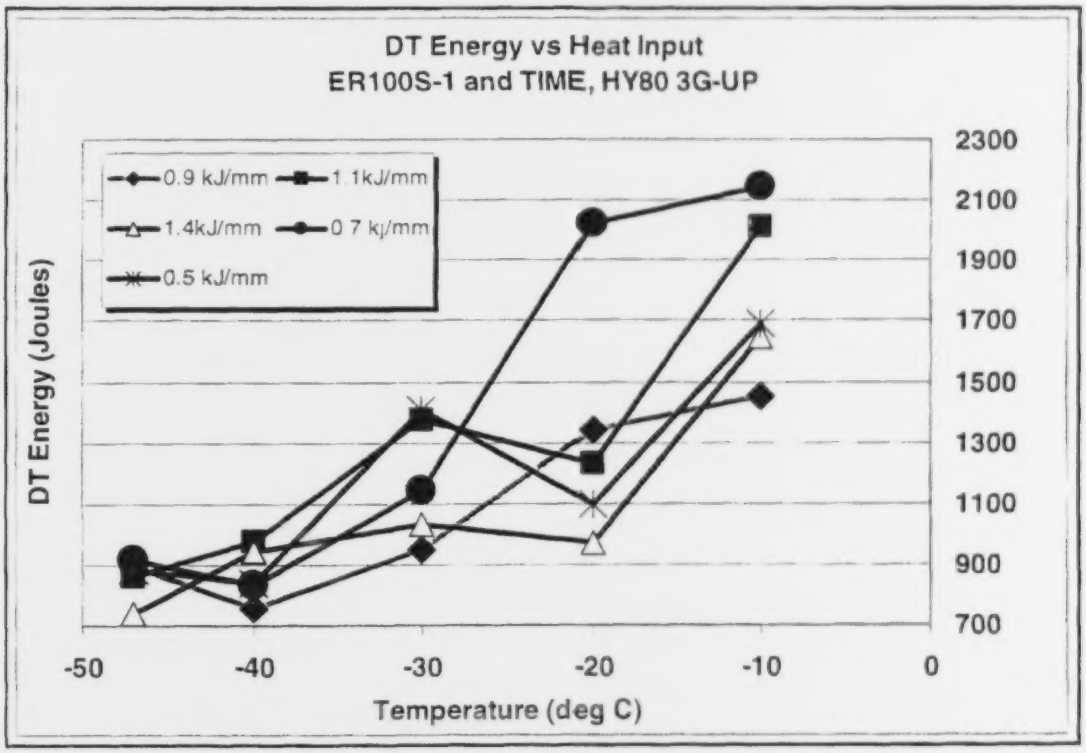

Figure 3.3: Weld Metal Dynamic Tear Energy vs. Heat Input

Because all the welds produced in this project were very tough the energy results are affected by the accuracy and quality of the pressed notch and this could explain the scatter seen in the energy results. The pressed notch is used to reduce crack initiation energy in the specimen so that the measured dynamic tear energy is predominantly propagation energy. Every attempt was made to

press each notch in an identical fashion, however, if the knife edges have a small variation in hardness or if they are at a slight tilt along the notch this can affect energy values, in extreme cases as much as 400 Joules.

Canadian and US Military specifications require the dynamic tear energy to exceed 690 J at –29°C, and all the welds meet this requirement.

Table 3.3: Weld Metal Notched Dynamic Tear Shear Lip Values

	Heat Input (kJ/mm)				
	0.5	0.7	0.9	1.1	1.4
Temp (°C)	Shear Lip (mm)				
-10	7.1	7.6	7.4	6.5	6.0
-20	4.9	6.61	7.5	5.9	5.0
-30	6.5	6.21	5.3	5.9	4 5
-40	5.3	5.0	4.6	4.7	4.0
-47	6.6	4.5	4.9	3.9	4.6
Average	6.08	5.98	5.94	5.38	4.82

The shear lip values shown in **Figure 3.4** show slightly less scatter when compared to the dynamic tear energy values. The reason for this is that energy values have errors associated with them that don't appear in shear lip and the shear lip is almost unaffected by the notch.

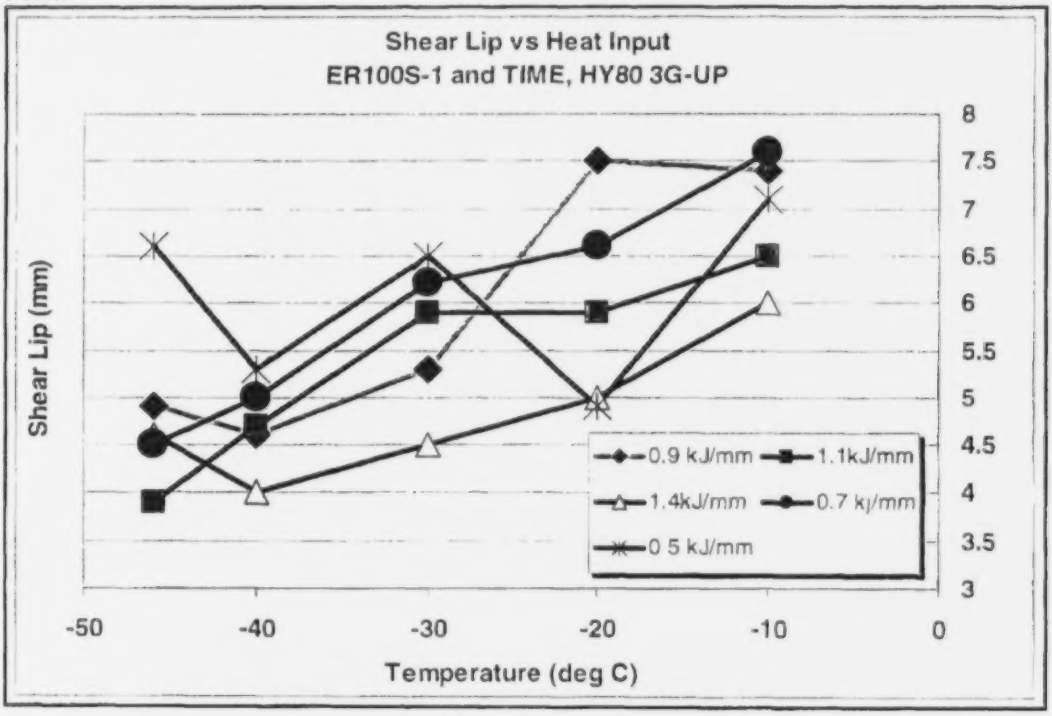

Figure 3.4: Shear Lip vs. Heat Input

Figure 3.5 averages the five values at each heat input which helps take out some of the scatter. There is still some scatter in the energy values as the energy is high at 0.7 and 1.1 kJ/mm, and low at 0.5 and 0 9 kJ/mm. This is most likely a notch effect and not a true toughness difference, however, there is a slight overall trend of decreasing dynamic tear energy with increasing heat input.

The shear lip is a much more reliable method of evaluating and comparing toughness and can be given more credibility that the dynamic tear energy levels. Based on the shear lip graph in **Figure 3.5**, there is a downward trend in toughness with increasing heat input and it starts around 1 kJ/mm.

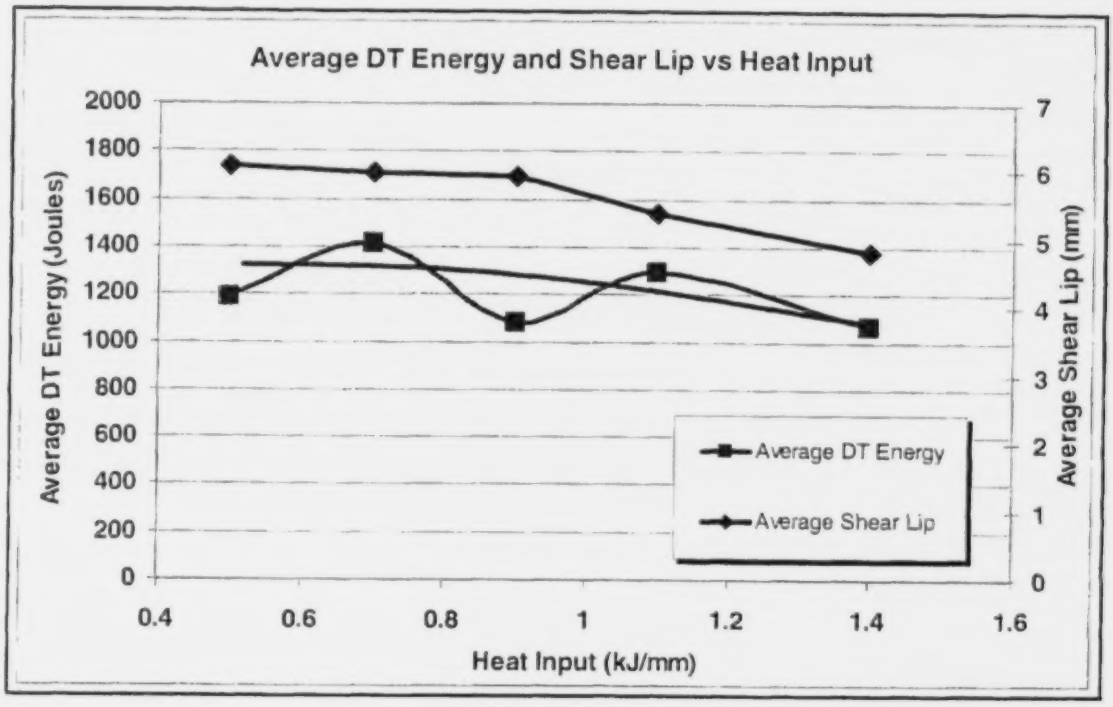

Figure 3.5: Average Dynamic Tear Energy and Shear Lip Values vs. Heat Input

Table 3.4: Heat Affected Zone Dynamic Tear Energy

	Heat Input (kJ/mm)				
	0.5	**0.7**	**0.9**	**1.1**	**1.4**
Temp (°C)	**HAZ Dynamic Tear Energy (J)**				
-10	1292	2357	1314	2256	2680
-30	1097	2017	1106	2445	2565
Average	1195	2187	1210	2351	2623

At first glance the heat affected zone dynamic tear energy results show a slight trend in increasing toughness with increasing heat input. However, due to the geometry of the double vee-groove, the notches in the specimens sampled only a small amount of heat affected zone, the rest being base material and weld metal. The observed range of the apparent HAZ toughness therefore, needs to be rationalized on the basis of the fracture path. Thus, the absorbed energy seems related to the amount of tougher base material in the fracture path as inferred from the following:

Heat Input	Test Temperature	Fracture Path
0.5 kJ/mm	-10°C	100 % Weld
	-30°C	100 % Weld
0.7 kJ/mm	-10°C	100% Fusion Line
	-30°C	33% Fusion Line, Balance Base Material
0.9 kJ/mm	-10°C	100% Weld
	-30°C	20% Fusion Line, Balance Weld Metal
1.1 kJ/mm	-10°C	75% Base and HAZ, Balance Base Material
	-30°C	50% Base and HAZ, Balance Base Material
1.4 kJ/mm	-10°C	100% Base Material
	-30°C	100% Base Material

This indicates that the corresponding dynamic tear energy values are high where the fracture path samples mostly the tougher base material, whereas the values are low where the fracture path samples mostly the less tough HAZ and/or weld metal.

Dynamic Tear Fracture Features

The fracture toughness of the weld metal was also compared by evaluating the features of the dynamic tear fracture surfaces (see **Figure 3.6**). For a given test temperature, as heat input decreases from 1.4 to 0.5 kJ/mm, the central flat region become very irregular (due to plastic deformation) indicating that the weld metal is becoming more notch ductile as heat input decreases. Based on the degree of plastic deformation, the 0.7 and 0.5 welds appear tougher than the others, and, the 0.5 kJ/mm being the toughest. The 0.7 and 0.5 kJ/mm heat input dynamic tear fracture surfaces at -20°C, **Figures 3.7 and 3.8** respectively, show two regular shear lips which gives way to a central flat region with grooves that look like internal shear lips trying to form. The lips are irregular from top to bottom of the specimen with what looks like two lips overlapped.

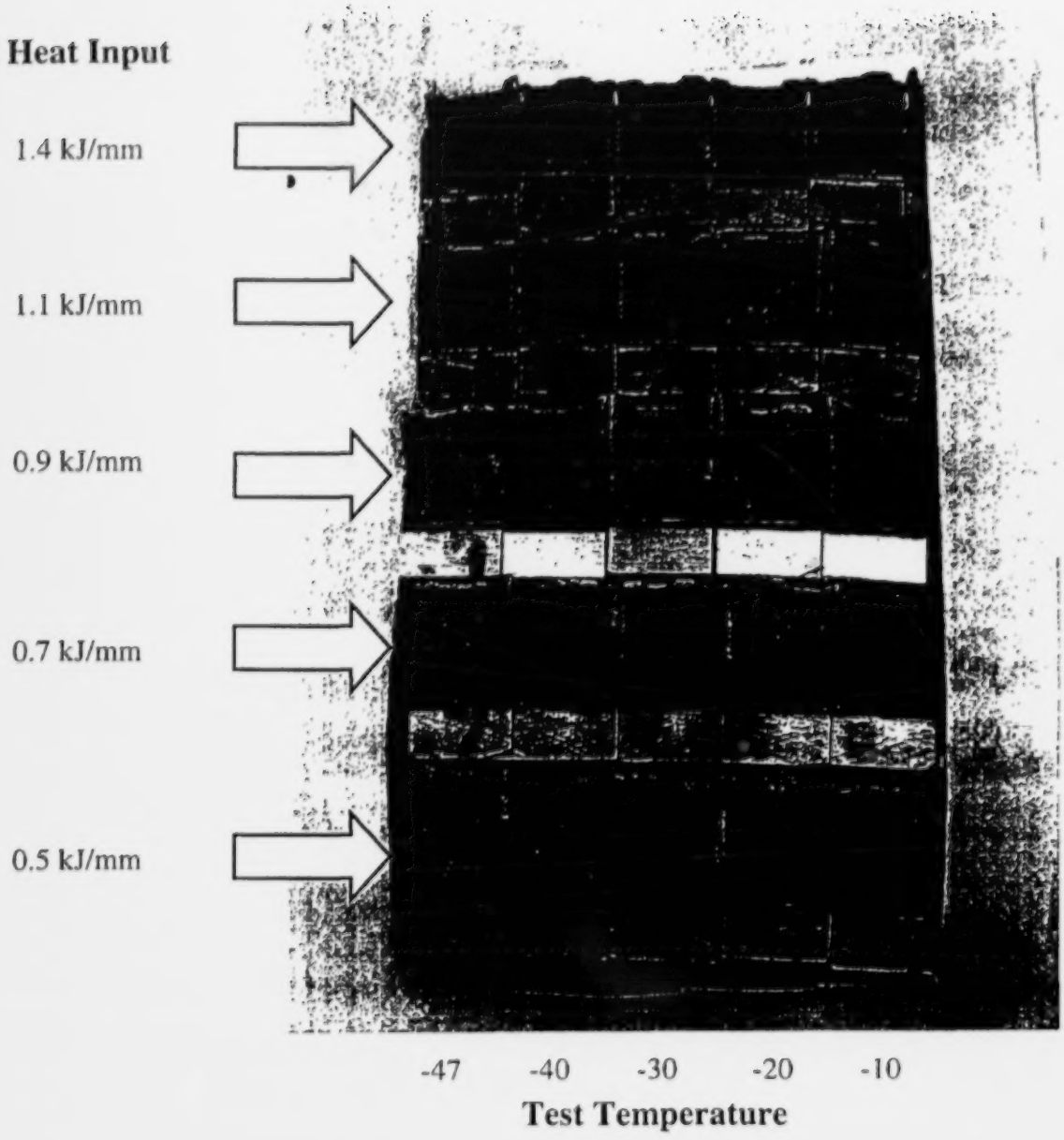

Figure 3.6: Dynamic Tear Fracture Surfaces

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Figure 3.7: 0.7 kJ/mm Dynamic Tear Fracture Surface, -20°C

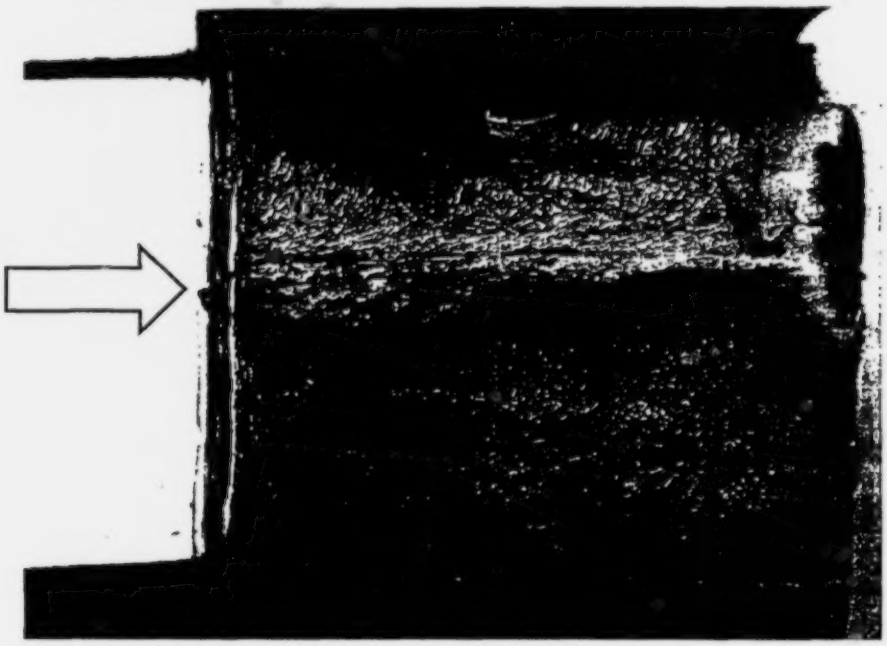

Figure 3.8: 0.5 kJ/mm Dynamic Tear Fracture Surface, -20°C

4. SUMMARY AND CONCLUSIONS

Five 1000 mm long 25 mm thick HY-80 panels were fabricated in the 3G vertical-up position with Lincoln's 1.2 mm LA100 (ER100S-1) solid wire and T.I.M.E gas. Each panel was welded with weld passes of a constant heat input and the range of heat inputs that were tested was 0.5 to 1.4 kJ/mm, and, the heat input levels were 0.5, 0.7, 0.9, 1.1, and 1.4 kJ/mm.

The radiography results showed that the 0.7, 0.9, 1.1, 1.4 kJ/mm panels were free of cracks and lack of fusion type indications, however, the 0.5 kJ/mm panel contained sporadic lack of fusion type indications. It is likely that the high travel speed and reduced wetting action of the weld pool at the 0.5 kJ/mm heat input level was the cause of the lack of fusion flaws, and, this level of heat input is not recommended for this application.

Weld cross sections were extracted from each heat input to characterize the effect heat input has on weld metal hardness. Results showed an overall trend in decreasing hardness with increasing heat input.

Five nominally full thickness dynamic tear specimens were machined from each weld heat input and were notched in the through thickness orientation at the weld centerline as per ASTM Standard E604. Two additional full thickness dynamic tear specimens were machined from each weld heat input and were notched in the through thickness orientation at the heat affected zone at the mid thickness location. All dynamic tear specimens were tested at the Dockyard Laboratories (DREA).

It is concluded from these observations that:

(i.) Based on the hardness results there is a downward trend in weld metal hardness with increasing welding heat input.
(ii.) Based on the shear lip results, there is a downward trend in toughness around 1 kJ/mm.
(iii.) Based on visual appearances, the 0.5 and 0.7 kJ/mm weld metals are tougher that at other heat inputs with the 0.5 kJ/mm weld being the toughest.
(iv.) All welds produced in this project exceed the minimum 690 J at -30°C CF toughness requirement.
(v.) Although the 0.5 to 1.0 kJ/mm heat input range produced the best toughness over the range of heat inputs tested, the heat input range of 0.7 to 1.1 kJ/mm tested provides the best operating range for 3G vertical-up welding with the Miller Phoenix power source.

5. RECOMMENDATIONS

Based on the findings in this project, it is recommended to:

(i.) Analyze the microstructure of the completed welds to determine if there are any significant differences with increasing heat input. The microstructures could be compared to the weld metal toughness results based on grain size, inclusion content, phases, etc.
(ii.) Evaluate the weld metal toughness in the other positions (flat, horizontal, and overhead). Position of welding may influence the effectiveness of shielding gas coverage, thus influencing the percentage of nitrogen entrapped in the weld metal and resulting toughness.

APPENDIX A

Welding Procedure Data Sheets

FTL FLEET TECHNOLOGY LTD
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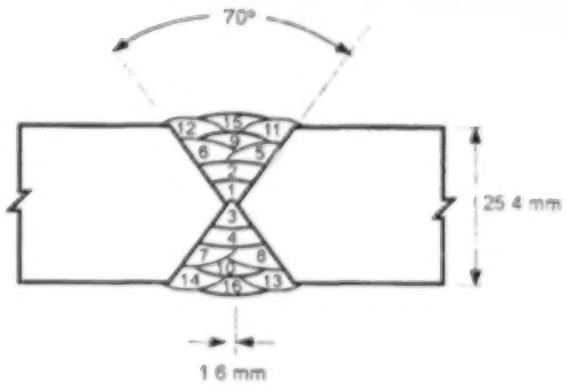
Welding Procedure Data Sheet

WPS No

WPDS No FTL-0 5 kJ/mm

Welding Process	P-GMAW
Electrode Type	Solid Wire
Filler Metal Classification	ER100S-1
Material Specification	HY80
Preheat Temperature(°C)	90
Interpass Temperature (°C):	120
Preheat Method	Ceramic Heaters
Position of Welding	3G
Travel Direction	UP
Polarity	DCEP
Shielding Gas	T I M E
Flow Rate (cfh)	50
Nozzle Orifice Size(mm)	19
Manual, Semi-Auto, Auto:	SemiAuto
Single or Multiple Arc	Single
Single or Multipass	Multipass
Root Treatment	Backgrnd 2 mm Minimum to Sound Weld Metal



Weld Sequence			Electrode Size		Wire Feed Speed		Amps	Volts	ESO		Travel Speed		Heat Input	
Side	Layer	Pass	mm	in's	mm/min	in/min	A	V	mm	in's	mm/min	in/min	kJ/mm	kJ/in
1	1	1	1 14	045	3300	130	100	18 8	16	6	203 2	8	0 56	15 2
1	2	2	1 14	045	3300	130	98	18 7	16	6	203 2	8	0 54	12 7
2	1	3	1 14	045	3050	120	98	18 4	12 7	5	203 2	8	0 53	12 7
2	2	4	1 14	045	3050	120	100 9	18 6	12 7	5	203 2	8	0 55	15 2
1	3	5	1 14	045	3050	120	93 5	18 4	12 7	5	203 2	8	0 51	12 7
1	3	6	1 14	045	3050	120	95 4	18 4	12 7	5	203 2	8	0 52	12 7
2	3	7	1 14	045	3050	120	97 7	18 3	12 7	5	203 2	8	0 53	12 7
2	3	8	1 14	045	3050	120	97 4	18 8	12 7	5	203 2	8	0 54	12 7
1	4	9	1 14	045	3050	120	95 2	17 9	12 7	5	203 2	8	0 50	12 7
1	4	10	1 14	045	3050	120	94 9	17 8	12 7	5	203 2	8	0 50	12 7
1	4	11	1 14	045	3050	120	95 4	18 2	12 7	5	203 2	8	0 51	12 7
2	4	12	1 14	045	3050	120	99 4	19 1	12 7	5	203 2	8	0 56	15 2
2	4	13	1 14	045	3050	120	102 3	17 5	12 7	5	203 2	8	0 53	12 7
2	4	14	1 14	045	3050	120	103 6	18 1	12 7	5	203 2	8	0 55	15 2
1	5	15	1 14	045	2665	105	92 8	17 2	12 7	5	177 8	7	0 54	12 7
2	5	16	1 14	045	2665	105	92 7	17 8	12 7	5	177 8	7	0 56	15 2

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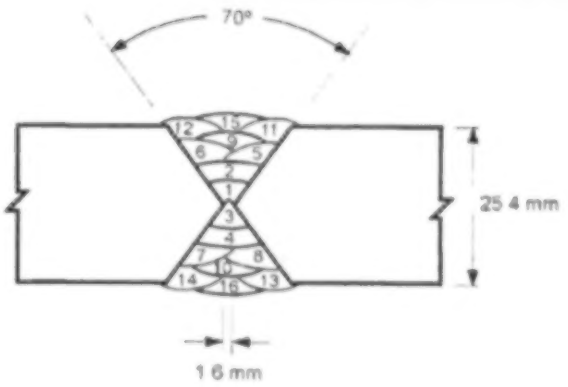
Welding Procedure Data Sheet

WPS No

WPDS No FTL-0 7 kJ/mm

Welding Process	P-GMAW
Electrode Type	Solid Wire
Filler Metal Classification	ER100S-1
Material Specification	HY-80
Preheat Temperature(°C)	90
Interpass Temperature (°C)	120
Preheat Method	Ceramic Heaters
Position of Welding	3G
Travel Direction	UP
Polarity	DCEP
Shielding Gas	T I M E
Flow Rate (cfh)	50
Nozzle Orifice Size (mm)	19
Manual, Semi-Auto, Auto	Semi-Auto
Single or Multiple Arc	Single
Single or Multipass	Multipass
Root Treatment	Backgrnd 2 mm Minimum to Sound Weld Metal



Weld Sequence			Electrode Size		Wire Feed Speed		Amps	Volts	ESO		Travel Speed		Heat Input	
Side	Layer	Pass	mm	in's	mm/min	in/min	A	V	mm	in's	mm/min	in/min	kJ/mm	kJ/in
1	1	1	1 14	045	3535	140	112 2	18 6	16	6	184 2	7 25	0 68	17 3
1	2	2	1 14	045	3300	130	117 1	17 9	16	6	184 2	7 25	0 68	17 3
2	1	3	1 14	045	3556	140	110 2	18 2	12 7	5	184 2	7 25	0 65	16 6
2	2	4	1 14	045	3300	130	112 5	18 6	12 7	5	184 2	7 25	0 68	17 3
1	3	5	1 14	045	3300	130	116 6	19 9	12 7	5	184 2	7 25	0 76	19 2
1	3	6	1 14	045	3300	130	115 6	19	12 7	5	184 2	7 25	0 72	18 2
2	3	7	1 14	045	3300	130	115 9	17	12 7	5	184 2	7 25	0 64	16 3
2	3	8	1 14	045	3300	130	118 8	18	12 7	5	184 2	7 25	0 70	17 7
1	4	9	1 14	045	3300	130	116 7	17 8	12 7	5	184 2	7 25	0 67	17 0
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2	4	12	1 14	045	3050	120	111 8	19 7	12 7	5	184 2	7 25	0 72	18 2
2	4	13	1 14	045	3050	120	109	19 4	12 7	5	184 2	7 25	0 69	17 5
2	4	14	1 14	045	3050	120	109	19 2	12 7	5	184 2	7 25	0 68	17 3
1	5	15	1 14	045	3050	120	104 7	18 1	12 7	5	171 5	7 25	0 66	16 8
2	5	16	1 14	045	3050	120	101 3	17 6	12 7	5	171 5	7 25	0 62	15 8

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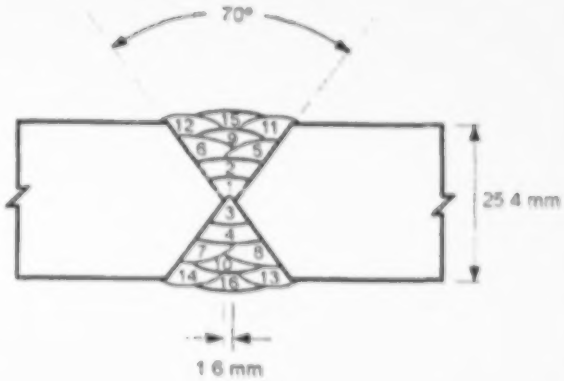
Welding Procedure Data Sheet

WPS No

WPDS No FTL-0 9 kJ/mm

Welding Process	P-GMAW
Electrode Type	Solid Wire
Filler Metal Classification	ER100S-1
Material Specification	HY-80
Preheat Temperature(°C)	90
Interpass Temperature (°C)	120
Preheat Method	Ceramic Heaters
Position of Welding	3G
Travel Direction	UP
Polarity	DCEP
Shielding Gas	T I M E
Flow Rate (cfh)	50
Nozzle Orifice Size (mm)	19
Manual, Semi-Auto, Auto	Semi-Auto
Single or Multiple Arc	Single
Single or Multipass	Multipass
Root Treatment	Backgrnd 2 mm Minimum to Sound Weld Metal



Weld Sequence			Electrode Size		Wire Feed Speed		Amps	Volts	ESO		Travel Speed		Heat Input	
Side	Layer	Pass	mm	in's	mm/min	in/min	A	V	mm	in's	mm/min	in/min	kJ/mm	kJ/in
1	1	1	1 14	045	3555	140	112	18 6	16	6	140	5 5	0 89	22 7
1	2	2	1 14	045	3300	130	117	17 9	16	6	140	5 5	0 85	22 5
2	1	3	1 14	045	3555	140	110	18 2	12 7	5	140	5 5	0 85	21 5
2	2	4	1 14	045	3300	130	112 5	18 6	12 7	5	140	5 5	0 90	22 8
1	3	5	1 14	045	3300	130	116 5	19 9	12 7	5	140	5 5	0 99	25 2
1	3	6	1 14	045	3300	130	116	19	12 7	5	140	5 5	0 91	23 0
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1	4	9	1 14	045	3300	130	117	17 6	12 7	5	140	5 5	0 88	22 4
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1	4	11	1 14	045	3050	120	112 4	19 5	12 7	5	140	5 5	0 94	23 9
2	4	12	1 14	045	3050	120	112	18 7	12 7	5	140	5 5	0 93	24 0
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1	5	15	1 14	045	3050	120	104 5	18 1	12 7	5	125	5	0 91	23 1
2	5	16	1 14	045	3050	120	101 5	17 6	12 7	5	125	5	0 86	21 8

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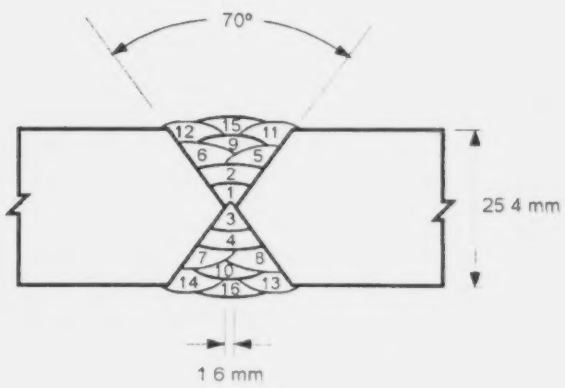
Welding Procedure Data Sheet

WPS No

WPDS No FTL-1 1 kJ/mm

Welding Process P-GMAW	Electrode Type Solid Wire
Filler Metal Classification ER100S-1	
Material Specification HY-80	
Preheat Temperature(°C) 90	
Interpass Temperature (°C) 120	
Preheat Method Ceramic Heaters	
Position of Welding 3G	Travel Direction UP
Polarity DCEP	
Shielding Gas T I M E	Flow Rate (cfh) 50
Nozzle Orifice Size (mm) 19	
Manual, SemrAuto, Auto SemrAuto	
Single or Multiple Arc Single	
Single or Multipass Multipass	
Root Treatment Backgrind 2 mm Minimum to Sound Weld Metal	



Weld Sequence			Electrode Size		Wire Feed Speed		Amps	Volts	ESO		Travel Speed		Heat Input	
Side	Layer	Pass	mm	in's	mm/min	in/min	A	V	mm	in's	mm/min	in/min	kJ/mm	kJ/in
1	1	1	1 14	045	3300	130	113 4	18 7	16	6	114 3	4 5	1 11	28 3
1	2	2	1 14	045	3175	125	115 5	18 7	16	6	114 3	4 5	1 13	28 8
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1	4	9	1 14	045	3175	125	107 9	19 1	12 7	5	114 3	4 5	1 08	27 5
1	4	10	1 14	045	3175	125	105	19 2	12 7	5	114 3	4 5	1 06	26 9
1	4	11	1 14	045	3050	120	108 1	19	12 7	5	114 3	4 5	1 08	27 4
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1	5	15	1 14	045	3050	120	107 2	18 7	12 7	5	88 9	3 5	1 35	34 4
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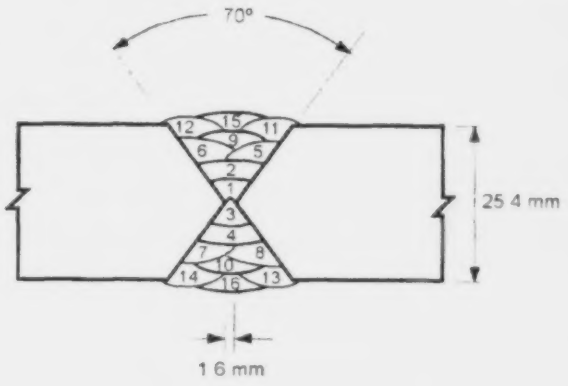
Welding Procedure Data Sheet

WPS No

WPDS No FTL 1 4 kJ/mm

Welding Process	P-GMAW
Electrode Type	Solid Wire
Filler Metal Classification	ER100S-1
Material Specification	HY-80
Preheat Temperature (°C)	90
Interpass Temperature (°C)	120
Preheat Method	Ceramic Heaters
Position of Welding	3G
Travel Direction	UP
Polarity	DCEP
Shielding Gas	T I M E
Flow Rate (cfh)	50
Nozzle Orifice Size (mm)	19
Manual, SemiAuto, Auto	SemiAuto
Single or Multiple Arc	Single
Single or Multipass	Multipass
Root Treatment	Backgrind 2 mm Minimum to Sound Weld Metal



Weld Sequence			Electrode Size		Wire Feed Speed		Amps	Volts	ESO		Travel Speed		Heat Input	
Side	Layer	Pass	mm	in's	mm/min	in/min	A	V	mm	in's	mm/min	in/min	kJ/mm	kJ/in
1	1	1	1 14	045	4575	180	128 2	21 5	16	6	114 3	4 5	1 15	[illegible]
1	2	2	1 14	045	4065	160	114 6	20 9	16	6	114 3	4 5	1 26	[illegible]
2	1	3	1 14	045	4575	180	127 1	21 2	12 7	5	114 3	4 5	1 41	[illegible]
2	2	4	1 14	045	4065	160	122 5	20 8	12 7	5	114 3	4 5	1 31	[illegible]
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1	3	6	1 14	045	4065	160	126 2	21	12 7	5	114 3	4 5	1 39	[illegible]
2	3	7	1 14	045	4065	160	122 3	21	12 7	5	114 3	4 5	1 45	[illegible]
2	3	8	1 14	045	4065	160	119	21	12 7	5	114 3	4 5	1 41	[illegible]
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1	4	10	1 14	045	4065	160	126 9	21 2	12 7	5	114 3	4 5	1 41	[illegible]
1	4	11	1 14	045	3430	135	115 7	21	12 7	5	114 3	4 5	1 28	[illegible]
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4 AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Darren Begg

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Over the past decade, Defence Research Establishment Atlantic (DREA) has sponsored several projects related to "All Position Gas Metal Arc Welding" as part of their mandate to develop expertise in submarine materials and maintenance technology. These efforts have led to the identification of pulsed GMAW with C5, C10, or T.I.M.E gas combinations as the preferred ones from the perspective of superior weld zone mechanical properties in HY steels.

Previous work was successful in ranking new digital pulsed gas metal arc welding systems for optimal introduction in submarine refit followed by the development of a low heat input benchmark welding procedure for welding HY-80 steel in the vertical-up position, using Lincoln's LA100 (ER100S-1) solid wire with T.I.M.E gas (26.5%He, 8%CO_2, 0.5%O_2, and Argon bal.)

Although the benchmark is considered a practical procedure for the purposes of submarine repair and modification, it would be advantageous from the point of view of productivity to increase the heat input while maintaining the toughness requirements.

Five welded panels were produced with ER100S-1 solid wire and T.I.M.E gas, and radiographed +/- 20° to normal to verify weld soundness. The heat input used to produce each welded panel spanned the practical range for all position welding with the objective of identifying a level at which the weld metal toughness drops off below the required value. Dynamic tear samples were extracted and tested to develop notch toughness transition curves for each weld heat input.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. *Thesaurus of Engineering and Scientific Terms* (TEST) and that thesaurus-identified. If it not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title)

welding
GMAW
T.I.M.E. Welding
Heat input
100S1 wire

UNCLASSIFIED
SECURITY CLASSIFICATION OF FORM